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ABSTRACT

The present research addresses the issues of whether there exist certain cognitive skills that facilitate transfer, and whether such skills are themselves transferable across domains. Of primary concern is the instructability of such skills. The Systems Thinking and Curriculum Innovation Project (STACI) is a two-year research project testing the potentials and effects of using the systems approach to teach content specific knowledge and general problem solving skills. The content of existing high school science courses has been integrated with instruction and computer software that emphasize higher-order cognitive skills. The study also examines the effectiveness of using Structural Thinking Experimental Learning Laboratory with Animation (STELLA) to teach system dynamics and content knowledge. Four science teachers at a high school in Vermont are using STELLA and systems thinking in their courses. Teachers and researchers are working in a collaborative effort. The teachers' primary goal is to infuse the classes with systems thinking and to determine if the curriculum innovation is an effective way of teaching certain topics and skills; the researchers' goal is to document the curriculum innovation and to examine its cognitive consequences. A primary outcome of the project will be to disseminate information about the theory that underlies systems thinking and the methods by which the approach has been infused in the curricula. (BAE)

The Use of Simulations in Learning and Transfer of Higher-Order Cognitive Skills

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Virtually all learning is transfer (Voss, 1978). However, not all learners are equally likely to be able to transfer skills from one domain to another. Similarly, not all tasks (Doyle, 1983), instructional programs, or skills are likely to engender transfer. Numerous instructional programs have emphasized the development of skills deemed critical to general intellective performance (e.g., Feuerstein, 1979, 1980; Palincsar & Brown, 1984). The critical question with regard to these instructional programs is whether there exist certain cognitive skills that facilitate transfer, and whether such skills are themselves transferable across domains. A primary concern is the instructability of such skills.

Transfer has been described and assessed in two ways (Brown, Bransford, Ferrara, & Campione, 1983). The "static" approach asks whether a skill attained in some cognitive task will affect performance in a second task. This view is reflected in the work of Ferguson (1956) who regarded transfer as a mathematical function, with the change in performance on one task altering performance on another. Brown and colleagues, favoring the "dynamic" approach, are more interested in how that which has been acquired affects the learning of a second task.

Instructional programs have varied as to the targeted skills, but all are based on implicit models of the skilled learner. Two common findings have led to the training of general skills. First, skilled learners are more active in learning situations (e.g.,

Bransford, Stein, Shelton, & Owings, 1981), and second, the knowledge and skills of the able learner are decontextualized from the original learning context. That is, the skilled performer is able consciously to access known skills in a variety of contexts in a flexible manner (Campione & Brown, 1978; Rozin, 1976). It has been argued that poor cognitive performers often have more capabilities than they exhibit spontaneously (Flavell, 1970). Thus, training procedures have been designed with the aim of teaching skills that could be accessed successfully in multiple contexts, not just in the originally learned context. These procedures included training skills with an active involvement of the individual in strategy usage, an awareness of the nature of the strategy and how it facilitates learning, monitoring of strategy effectiveness, and a gradual transfer of control from the experimenter or instructor to the subject or student. This general sort of approach was advocated by Belmont, Butterfield, and Ferretti (1982), Borkowski and Cavanaugh (1979), Brown and Campione (1981), Campione and Brown (1978), Corno and Mandinach (1983), and Meichenbaum (1977, 1980, 1985).

These programs, which typically focus on a small number of self-regulatory skills, have been fairly successful in transference of a learned skill to novel contexts (Belmont et al., 1982). Skills have included recall readiness (Brown, Campione, & Barclay, 1979), elaboration of potentially arbitrary information (Franks, Vye, Auble, Mezynski, Perfetto, Bransford, Stein, & Littlefield, 1982; Kestner & Borkowski, 1979), and developing self-instruction techniques (Schleser, Meyers, & Cohen, 1981).

Many of these instructional programs are based on models of expert performance. It is critical to understand how both experts and novices perform differentially on specific tasks. It also is important to be able to include models of intermediate performance. As Heller and Reif (1984) note: "it is unwise to assume that the performance of experts is necessarily optimal. Furthermore, educational efforts cannot merely aim to teach students to perform as experts do. Instead, they must often teach students to use explicit procedures to accomplish tasks which experts perform almost automatically because of years of experience (p. 178)."

Rationale for Studying Transfer

The issue of transfer has been a prominent one in educational computing circles. Educators, administrators, and others seek to establish the link between computer-based learning activities, particularly programming, and more general problem solving skills. The argument is that teaching programming or using cognitively engaging simulations and software should foster the acquisition of higher cognitive skills. To date, however, there is little empirical evidence of transfer of higher-order skills either within computer learning environments or to other content areas.

Some general problems are prevalent in extant studies. First, the match between skills engendered by the computer and those hypothesized in the external environments are not necessarily parallel. Thus, it is difficult for students to recognize the similarities of the tasks' demand characteristics and apply the skills appropriately. Second, many computer-based learning activities, particularly initial instruction in programming, do not

require sufficiently complex cognitive skills. Instead, they require more content-specific knowledge and lower-order skills. Thus, the task demands are more declarative than procedural, and delimit the cross domain applicability. Finally and perhaps most importantly, instruction that accompanies many computer-based activities fails to make explicit the connections among tasks and how the targeted skills can be applied in other domains. One cannot expect transfer to occur spontaneously for most learners. Instead, students need assistance in making the connections and need to observe appropriate applications of the targeted skills.

The present research addresses these issues by examining the acquisition of higher-order cognitive skills and transfer. Learning and transfer are to be assessed as outcomes of classroom instruction in the high school sciences. The content of these courses have been integrated with instruction and computer software that emphasize higher-order cognitive skills.

The Systems Thinking and Curriculum Innovation Project

General Background Information

The Systems Thinking and Curriculum Innovation (STACI) project is a two-year research project conducted by Educational Testing Service under the auspices of the Educational Technology Center at the Harvard Graduate School of Education. The project is intended to examine the cognitive demands and consequences of learning from a systems thinking approach to instruction and from using simulation modeling software.

The purpose of the study is to test the potentials and effects of using the systems approach in existing secondary school

curricula to teach content-specific knowledge as well as general problem solving skills (e.g., self-regulation). The study also examines the effectiveness of using STELLA (Structural Thinking Experimental Learning Laboratory with Animation; Richmond, 1985) as a tool by which to teach system dynamics and content knowledge. The research focuses on (a) the learning outcomes and transfer that result from using such an approach and software in classroom settings, and (b) the general effects of teaching with the technology.

The study is being conducted at a high school in southern Vermont in which four teachers are using systems thinking in their courses. The course content areas include general physical science, biology, chemistry, and an experimental course entitled War and Revolution. These four teachers, trained to use STELLA and system dynamics, are using systems models and illustrating them on the computer.

The intent of the research project is to examine the extent to which students acquire higher-order cognitive skills through interaction with a curriculum infused with systems thinking concepts and subsequently generalize knowledge and skills to problem solving tasks in other substantive areas. Comparisons are being drawn between traditionally taught courses and those that use the systems approach and STELLA. Furthermore, the two-year duration of the research enables the examination of skill and knowledge transfer across content areas as students are exposed to several courses that use the systems approach.

Two ancillary studies are being conducted in conjunction with the main study. The first focuses on a select group of students who have received extensive exposure to systems thinking and STELLA. The objective of this study is to examine intensively the thought processes, performance patterns, and general problem solving skills of these students. The second substudy examines the organizational impact of the introduction and implementation of systems thinking in the high school. The objective is to analyze changes that occur in the structure and functioning of the educational organization as a result of the curriculum innovation.

Systems Thinking

The field of system dynamics provides a means to understand the behavior of complex phenomena over time. Several important concepts underlie system dynamics. First, the variables that characterize a system change over time. Furthermore, the relationships among variables are interconnected by cause-and-effect feedback loops. Thus, changes in the status of one or more variables subsequently affects the status of other variables.

System dynamics uses computer-based mathematical models to simulate complex relationships among variables (Forrester, 1968). It is possible to understand the rule-like behavior of structures by constructing models of variables and examining the interactive relationships among the variables. Simulation models are used to examine the structure of such systems. A simulation generally is a simplified representation of the operation of real-world systems over hypothetical time.

In order to build a simulation, it is necessary to identify the variables that comprise the system and the relationships among these variables. Using simulation software, characteristics of selected variables can be altered and their effects on other variables and the entire system assessed. Thus, system dynamics focuses on the connections among the elements of the system and provides a means to understand how the elements contribute to the whole (Roberts, Andersen, Deal, Garet, & Shaffer, 1983).

The principles that underlie the field of system dynamics form the basis for much of the simulation software that currently is used in educational settings. Applications range from using complex models to train business executives at the post-graduate level to precollege instruction in traditional content areas.

Until recently, the system dynamics approach to simulations was constrained to environments that had powerful mainframe computer systems. The advent of a new software product has made it possible to translate these concepts to the microcomputer level. STELLA capitalizes on the graphical capabilities of the Apple Macintosh^{TM} and enables learners to build systems models using mouse and icon technology. STELLA makes systems modeling approachable to the novice by minimizing the mathematical and technical skills needed to construct models. The user supplies the logic necessary to build the model and STELLA outputs structural diagrams, graphs, and data that represent the system. Thus, STELLA is a powerful software tool that enables students to build models and simulations within the context of a systems thinking approach to learning.

Site Description: Brattleboro Union High School

Brattleboro Union High School (BUHS) serves a rural five-town district in southeastern Vermont. BUHS has roughly 1,600 students and 80 faculty.

Systems thinking at BUHS. In 1984 a group was formed to develop a systems thinking program in Brattleboro. The group consisted of representatives from Dartmouth College, the University of Vermont, Massachusetts Institute of Technology, several private and public schools in Vermont, and private industry. Two workshops were an outgrowth of the group. The first was a one-day seminar given by two systems experts from MIT. The intent of the meeting was to provide sufficient knowledge of system dynamics to high school teachers so that they could integrate the concepts into their courses. The second workshop was an intensive five-day introduction to systems thinking. Taught by representatives from MIT and Dartmouth, this seminar was directed to BUHS teachers, students, parents, school board members, and individuals from local businesses.

BUHS continues to maintain a close collaborative relationship with systems experts. Some of the teachers have enrolled in college-level systems courses. MIT faculty also have come to BUHS to consult with the teachers and lecture in several courses.

Four teachers form the core of the systems group at BUHS. All received training in the systems approach and are integrating this perspective into their courses. One course, entitled War and Revolution, is an experimental class which is heavily infused with systems thinking and the use of STELLA. Students are learning

systems thinking as a means of analyzing the dynamics of historical and current events. While conducting independent research projects, students will use STELLA to develop and test their models of a political event.

A more integrative approach is used in the science courses. These courses cover the same body of knowledge taught in the traditional science curricula, but discussions of selected concepts and topics are supplemented with a systems thinking perspective. In these courses, students are learning concepts underlying model development and have an opportunity to experiment with existing models using STELLA. The teachers also plan to develop and introduce a new course entitled Science, Technology, and Society that will incorporate an extensive introduction to system dynamics and STELLA.

Curriculum issues. The process of introducing curriculum innovation demands substantial investment of time and energy. In the STACI project, the tools and concepts of system dynamics have been used in higher education but have not frequently been applied to instruction at the high school level. Although the BUHS teachers are experts in their subject areas, they must acquire knowledge and skills from the field of systems thinking in order to integrate this approach into their curricula. They must develop expertise not only in systems concepts, but also gain skill in using STELLA. Thus, amidst their existing responsibilities, these teachers must serve as curriculum developers.

Serving in this capacity, the teachers are confronted with a number of curriculum issues:

1. What sequence of knowledge should be followed in teaching systems thinking? What are the prerequisite skills or knowledge needed before introducing the next level of knowledge?

2. At what points in the curriculum can systems thinking best be used? Is systems thinking an effective way to teach particular concepts (in contrast to traditional instructional methods)?

3. How and when should STELLA be introduced?

Design and Instrumentation

Design. In order to respond to these questions, ETS is examining how systems thinking is being integrated into three general physical science, four biology, and three chemistry classes (see Table 1). An equivalent number of traditional classes, which will serve as a comparison group, are being taught concurrently by other members of the faculty.

Instrumentation. Several types of instruments will be used to assess outcomes in various stages of the research. These instruments can be separated into pretest, in-class, and posttest measures. They also can be separated according to targeted skills and knowledge. Instruments to assess ability, content-specific knowledge, systems thinking, and higher-order thinking skills will be administered.

Initial assessments of subjects' ability, content-specific knowledge, and systems thinking will be used. Standardized achievement test scores and a small reference battery will serve as rough estimates of general ability.

Previous final examinations in the sciences were modified and administered to both systems and traditional classes. These tests will serve as baselines of content-knowledge in the subject areas. An initial assessment of systems thinking also was administered to serve as a baseline for the experimental classes.

Teachers will administer content-specific tests in their courses throughout the academic year. Thus, we will be able to compare differences in content knowledge in the systems and traditional courses.

ETS and BUHS are working with experts from MIT to develop measures of systems thinking that can be used in the various courses. These measures, reflecting the concepts emphasized in the instruction, focus on concepts such as knowledge of graphing, equations, variation and variables, causation and causality, feedback, and looping constructs.

Posttests of content knowledge, systems thinking, and general problem solving will be developed. Common final examinations will serve as measures of content knowledge. The systems posttest will in part, require the students to design a model for a small system as a final project. Tests of general problem solving, metacognition, and self-regulation also will be administered.

Implementation Issues

One central issue has guided the ETS-BUHS interaction to date. Specifically, the project is a collaborative effort in which the researchers and teachers have been working toward mutually agreeable terms under which to conduct the study. Both parties

have had to specify in detail their roles, expectations, and goals for the project.

BUHS has undertaken an innovative curriculum project. The teachers are working extremely hard to develop and implement curricula, while also having to carry out all of their regular duties. Curriculum development is time consuming and difficult, particularly when it is attempted with courses in progress. A paraprofessional, hired under the auspices of the project, is providing release time so that the teachers can concentrate on substantive issues rather than administrative duties.

The teachers' primary goal is to infuse the classes with systems thinking and determine if the curriculum innovation is an effective way of teaching certain topics and skills. They acknowledge that systems thinking is not appropriate for all parts of their courses, but that perhaps it will be a better instructional tool for particular concepts. Thus, a secondary goal is to identify those concepts and content areas that might benefit from the approach. The ultimate goal of the project, from the perspective of the BUHS teachers, is to develop and implement curriculum materials that will enhance both the content knowledge and thinking skills of their students. The test of the project's success will be to determine if systems thinking improves students' learning in the targeted classes.

The researchers' goal is to document the curriculum innovation and examine its cognitive consequences. Thus, from the research perspective, data collection and design are critical issues. However, curriculum development and the ensuing data collection are

not necessarily complementary events. Curriculum development is an ongoing effort. ETS is cognizant that during this first year, as systems thinking is being introduced, the teachers will be experimenting with instructional methods and course content. Thus, the first year will be seen as an exploratory phase of data collection. Once sufficient curricular revisions are in effect, ETS then can implement a systematic research design to examine their impact.

Both researchers and teachers will benefit from the collaborative effort. A primary outcome of the project will be to disseminate information about the theory that underlies systems thinking and the methods by which the approach has been infused in the curricula. Information about the organizational impact of the innovations also should be useful. Dissemination of project results will inform other educators of the potentials of the systems thinking approach and enable them to adapt the curricula according to the needs of their institutions. The BUHS teachers will have developed and implemented innovative curricula that could have a positive impact on other high school science programs. ETS will have helped to examine, analyze, and document that impact and the cognitive consequences of teaching with a systems thinking approach and simulation modeling software.

Footnote

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Table 1

Targeted Classes and Enrollment Figures

Class	Systems Thinking		Traditional	
	Classes	Students	Classes	Students
General Physical Science	3	47	3	69
Biology				
Teacher 1	4	82	2	55
Teacher 2			2	39
	4	82	4	94
Chemistry	3	63	3	64
TOTAL	10	192	10	227
War and Revolution	1	9		